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Webinar: Electric Bus Deployment: Cost and Environmental Equity

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An Electric Bus Deployment Framework for Improved Air Quality and Transit Operational Efficiency

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Project Briefing

- NITC Project No. 1222
- Built upon a previous research effort sponsored by the Utah Transit Authority (UTA)
- Motivated by the need to support transition of the transit fleet to the lowest polluting and most energy efficient transit vehicles

Introduction

Previous Effort

Visualization

NITC project

Introduction

Previous Effort

NITC project

Visualization

1 Introduction

- Battery-electric buses (BEB) demonstrated average efficiency of 2.15 kWh per mile, which translates to about 17.48 miles per diesel gallon equivalent (DGE). The CNG buses used for comparison had an average fuel economy of just 4.51 DGE.

- Battery-electric buses' operation requires supporting infrastructures: on-route fast charging and in-depot charging.

1 Introduction

How to spatially and temporally integrate BEBs into current public transit system without interference with current operation routes and schedules?

Transit system has unique spatio-temporal characteristics:

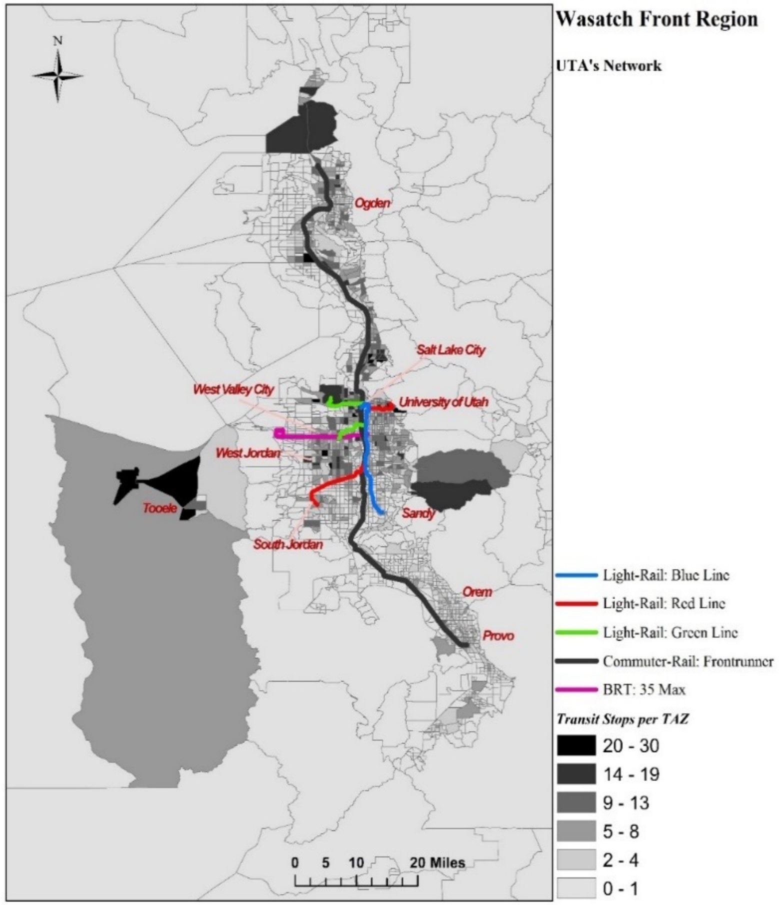
- **Require periodic on-route charging at bus terminal and overnight charging at bus garages**
- **Space-time trajectories of BEBs should fit into current transit operation routes and schedule**

Introduction

How to deploy the battery electric buses with minimum costs while also benefiting people in need?

- Social functions depend highly upon the transit system

- **Requires a phased approach with varying budgets**
- **Disadvantaged populations are transit dependent and particularly vulnerable to air pollution.**
- **To benefit the disadvantaged population suffered most from air pollution when deploying BEB.**



Objectives

- **Develop a spatio-temporal analytical framework to assist transit agencies in identifying the optimal deployment for the BEB system**

- **Optimizing BEB deployment considering cost and environmental equity for disadvantaged population**

Introduction

Previous Effort

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Previous Effort

Develop a spatio-temporal analytical framework to assist transit agencies in identifying the optimal deployment for the BEB system

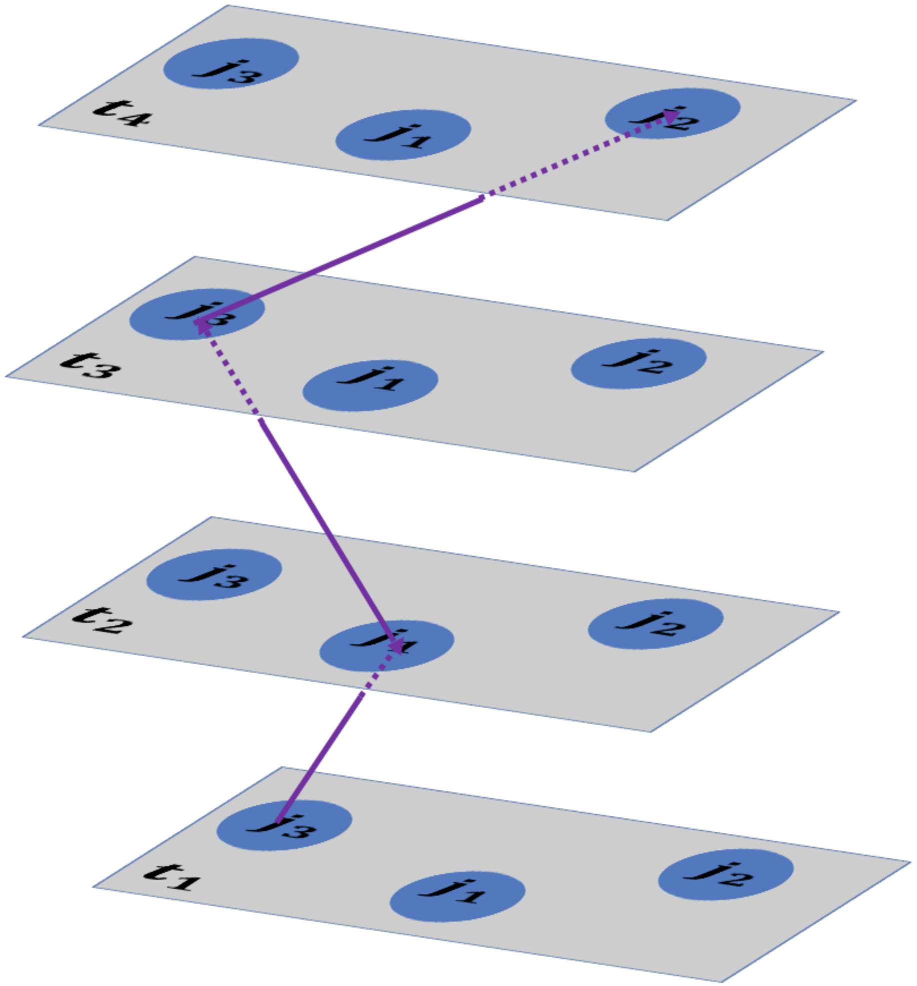
$$\min(\boxed{\sum_j c_j^R Y_j^R + \sum_g c_g^G Y_g^G} + \boxed{\sum_i f Z_i)}$$

- **Objective (0):** Minimizing the total cost of:
  - – In-depot and On-route Charging stations
  - – Battery Electric Buses (BEB)
- **Input:** Number of buses to be replaced with BEB
- **Output:**

1. Locations and number of both in-depot and on-route charging stations.
2. The exact buses that were to be replaced.

Previous Effort

Consider each bus is running through a sequence of terminals, indexed by j, temporal period indexed by t defined as bus arrival time at each terminal
j3->j1->j3-j2



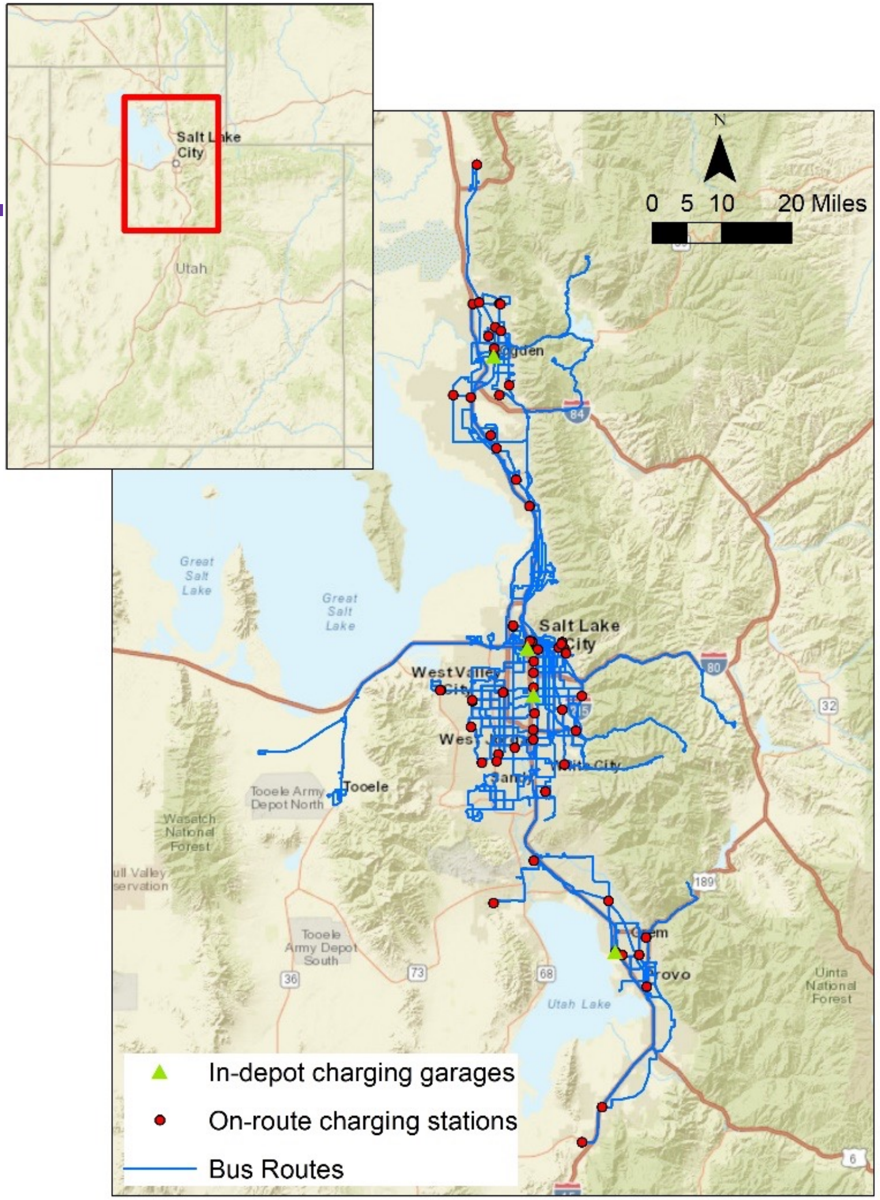
Wei, R., Liu, X., Ou, Y., & Fayyaz, S. K. (2018). Optimizing the spatio-temporal deployment of battery electric bus system. *Journal of Transport Geography*, *68*, 160-168.

2 Previous Effort

- 467 diesel or CNG buses that serve 121 fixed and flexible bus routes on a typical weekday within UTA’s network. Many of these buses are running across multiple bus routes as UTA employs vehicle interlining to reduce operating cost
- Proterra
  - 35-foot catalyst FC+ model
  - Nominal range: 62 miles
  - Charging:
    - On-route fast charging: 10-13min, charge 6 FC+ simultaneously
    - In-depot charging: overnight, charge 12 FC+ simultaneously

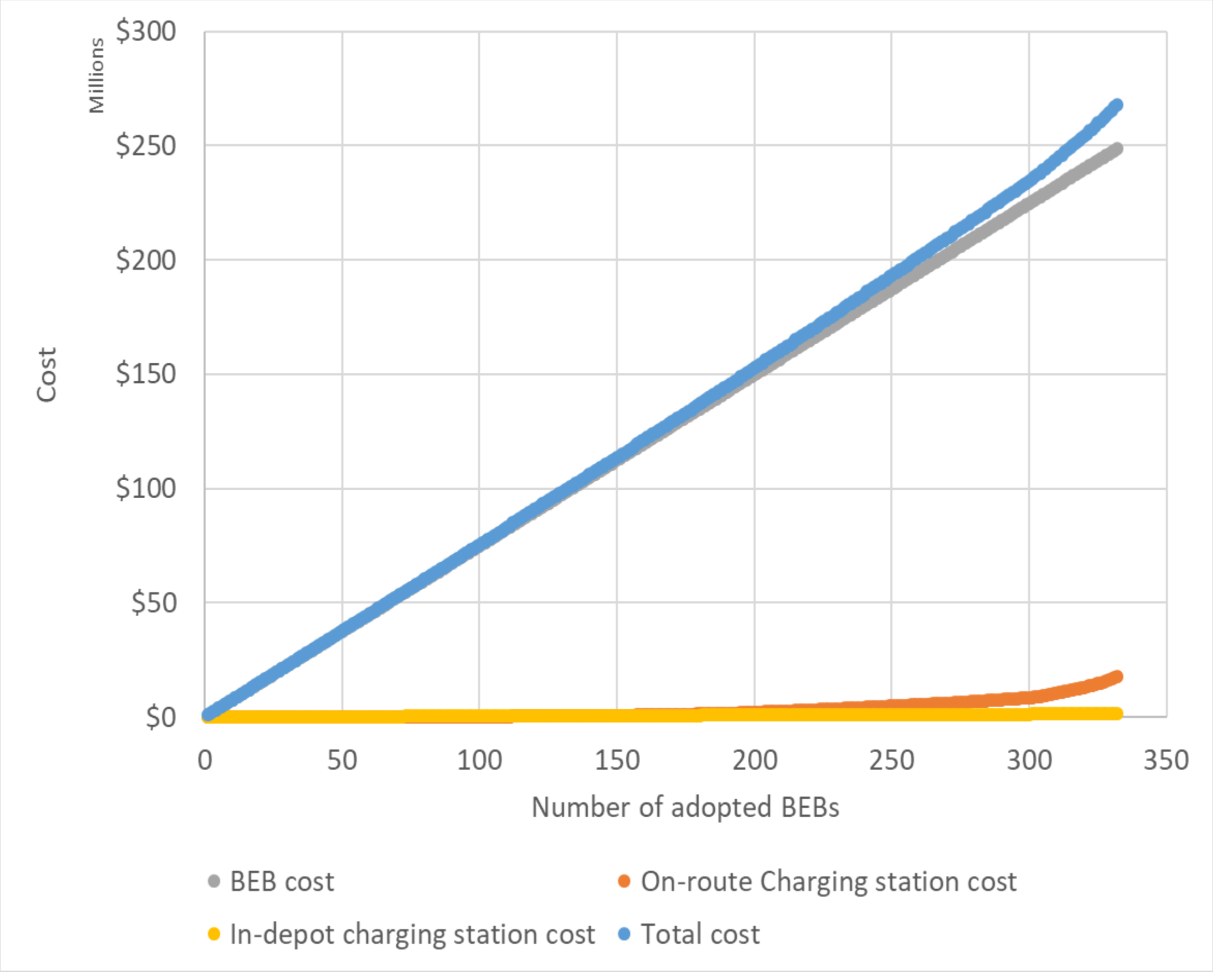
2 Previous Effort

- 135 existing buses will not be able to get charged before running out of battery if they are replaced with the FC+ BEBs (leave **332** potential replacement cases)
- Cost of a FC+ BEB $749,000, on-route charging station $499,000, in-depot charging station $50,000
- 70 potential sites for on-route charging stations



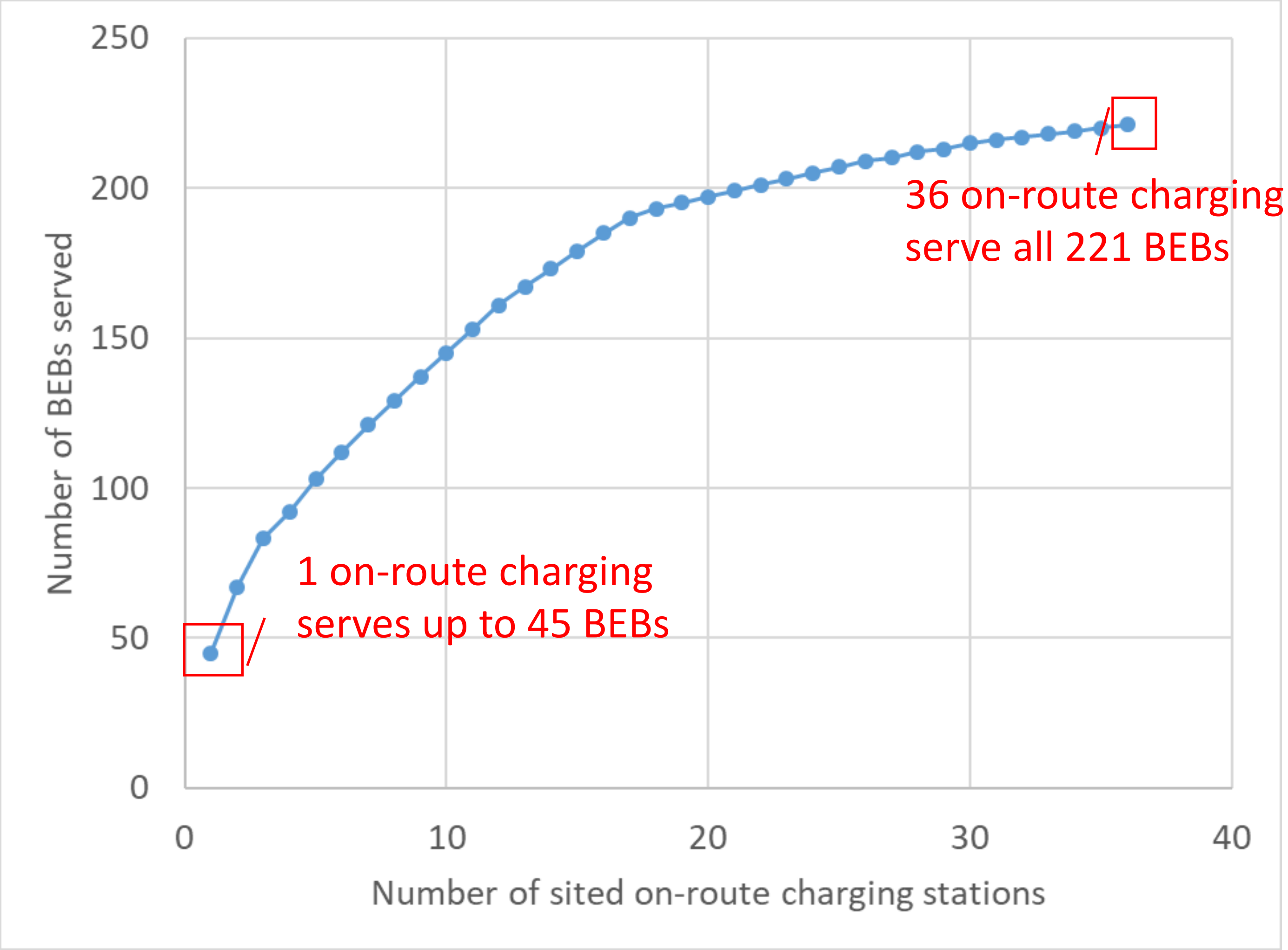
Previous Effort

- The strict linear relationship between the number of adopted BEBs and purchasing cost assuming no discount associated with the size of order
- No need to install on-route charging stations until 111 buses are replaced with BEBs, with ten in-depot charging stations

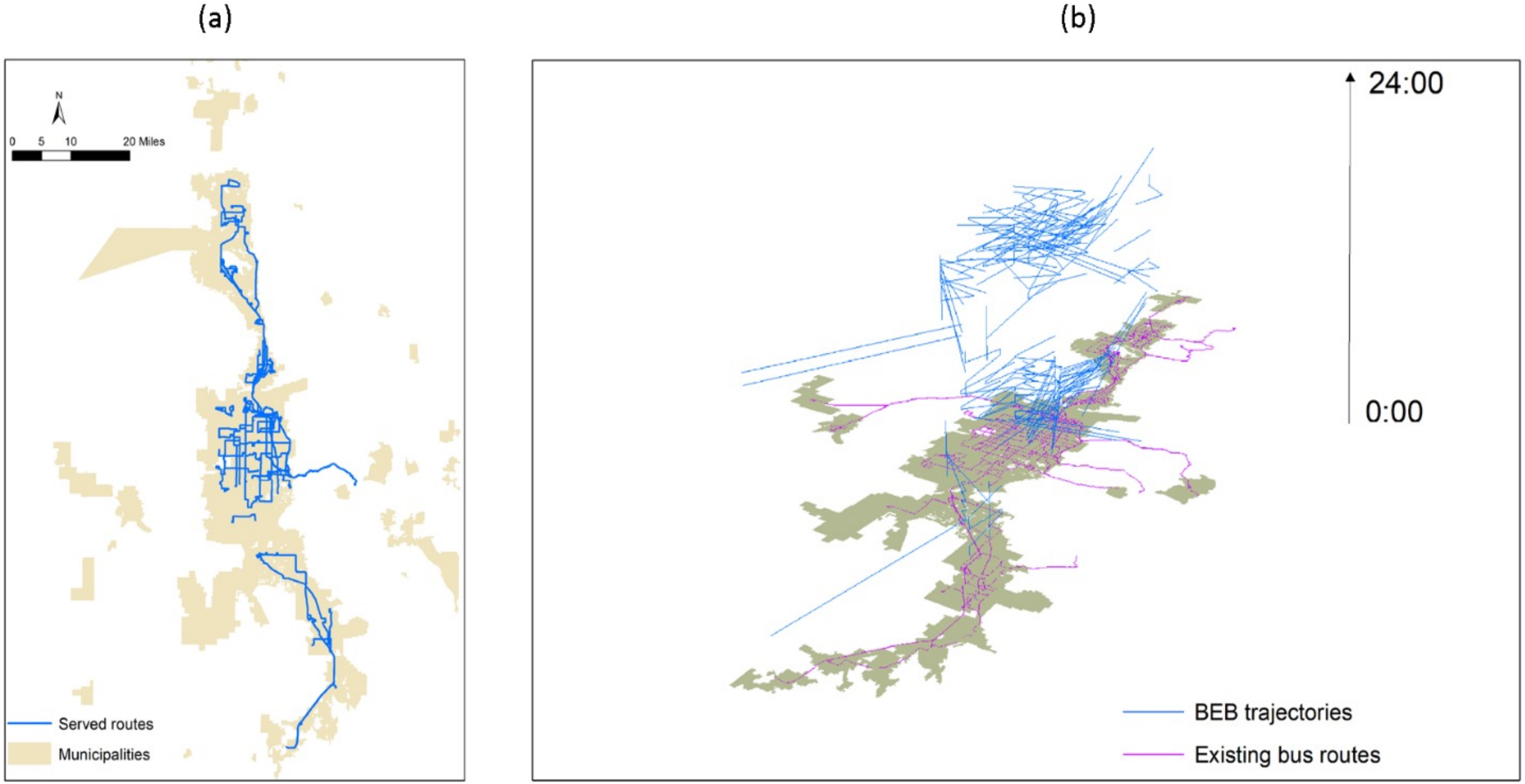


Previous Effort

- 221 (332-111) buses will need on-route charging
- The first on-route charging station can serve up to 45 additional BEBs
- 36 charging stations are enough to serve the entire 221 BEBs



Previous Effort

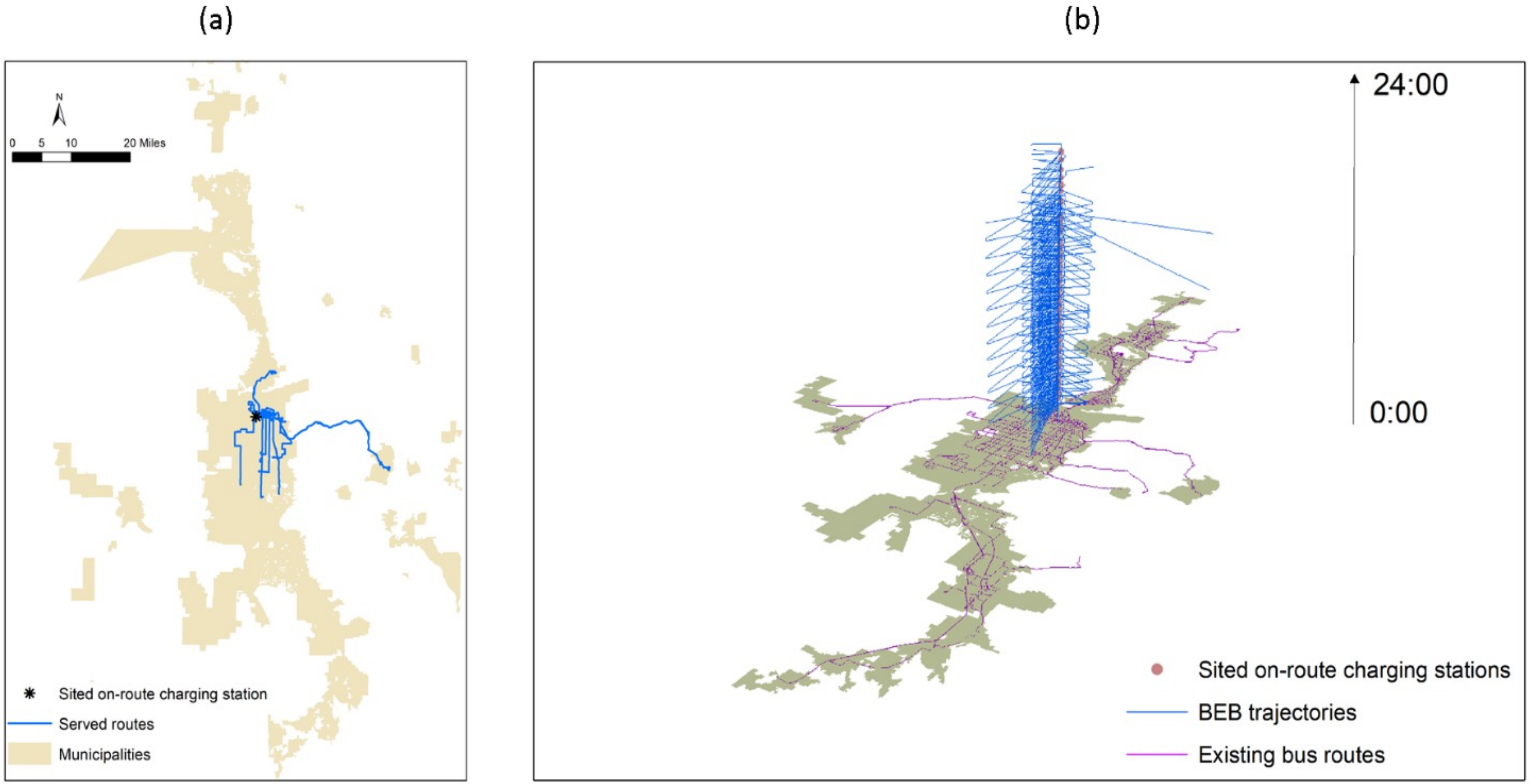


Daily mileage:
10-60 miles
51 bus routes

Long distance routes once or twice a day, or short routes multiple times

- ➢ Served routes and space-time trajectories of the 111 BEBs without requiring on-route charging

Previous Effort



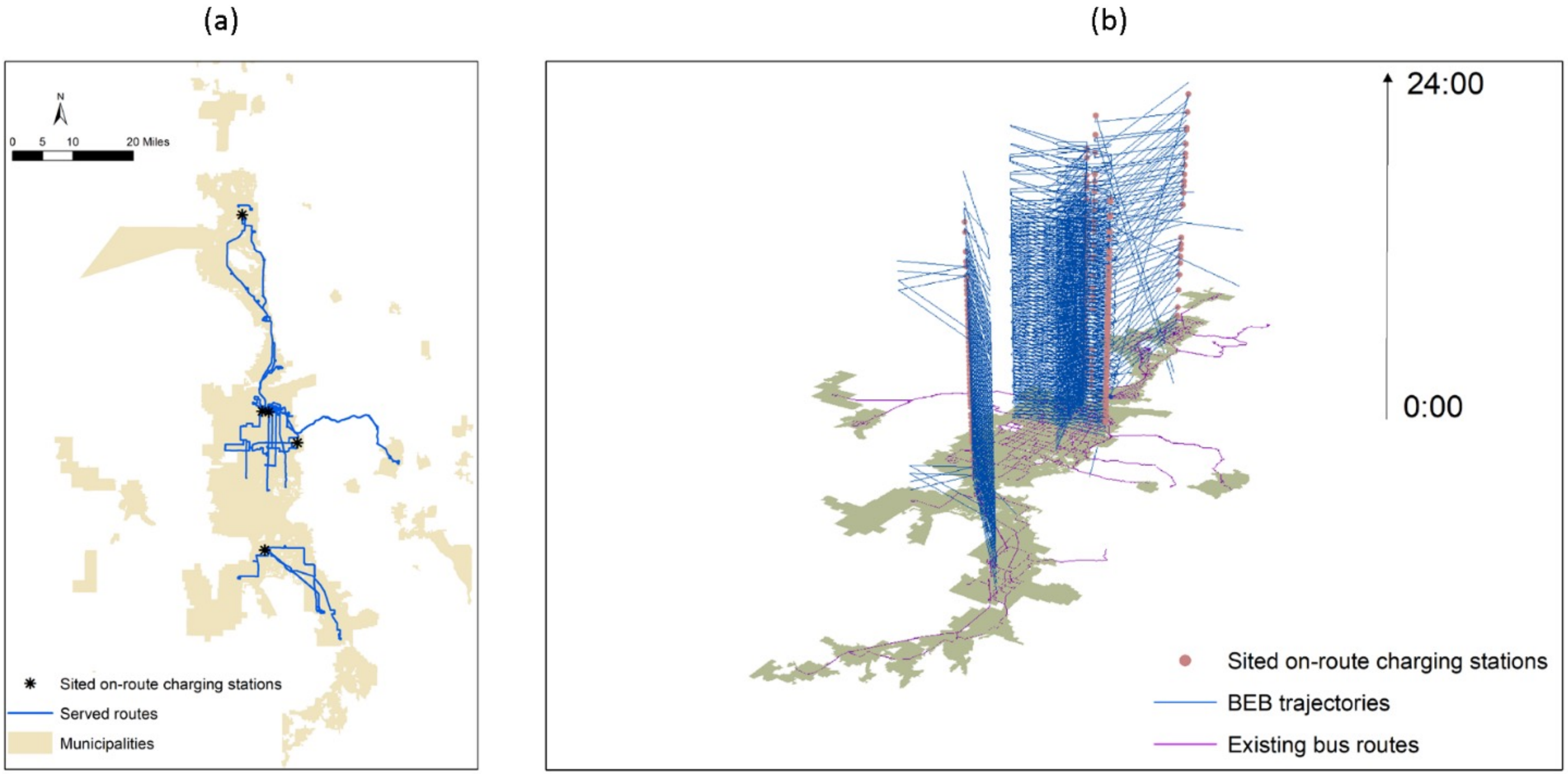
156 (111+45) BEBs

Daily mileage: 88-252 miles
16 additional bus routes

Provide charging for 318 times from 6:30 am to 21:50 pm

➢ Served routes and space-time trajectories of BEBs when one on-route charging station is built

Previous Effort



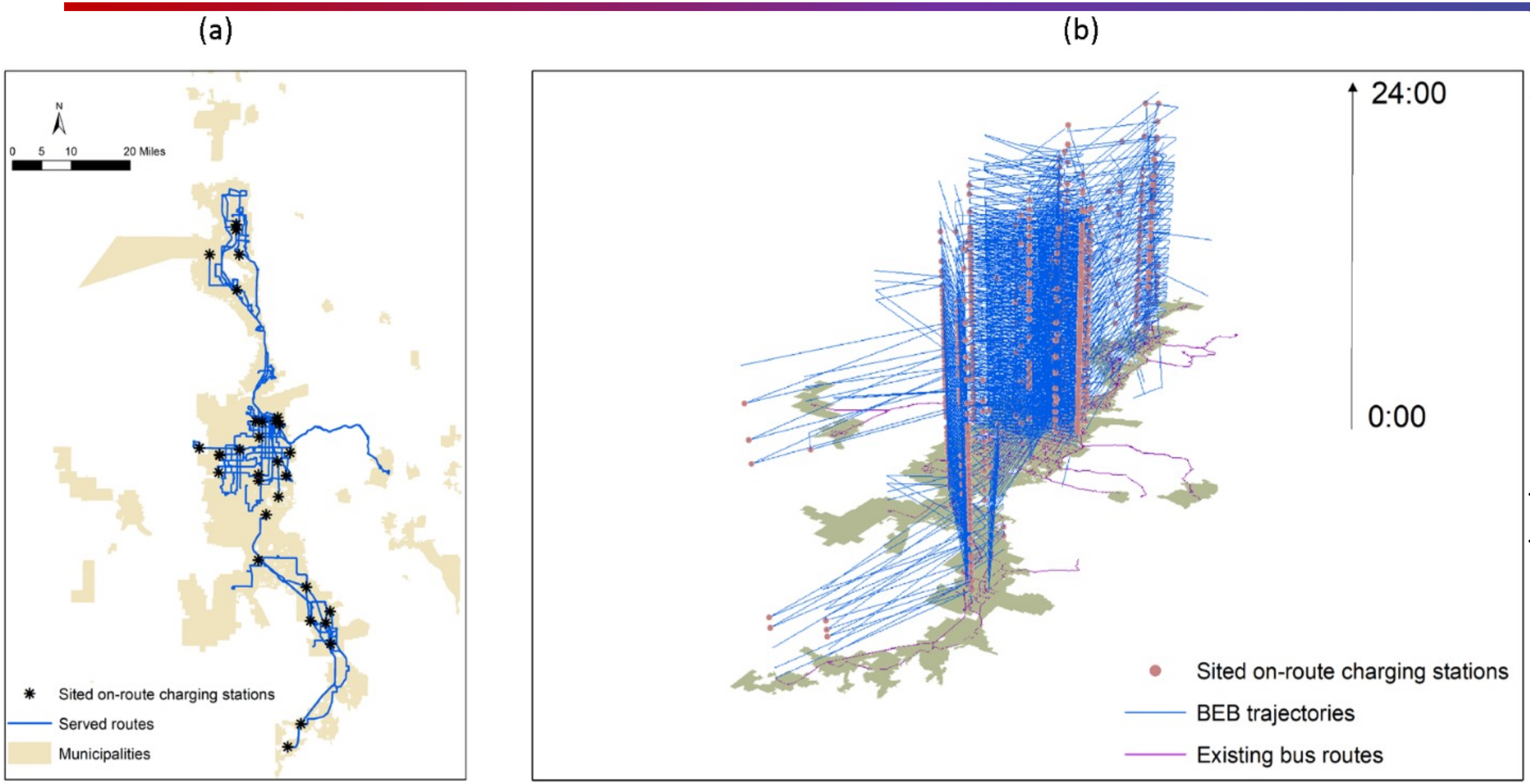
214 (111+103) BEBs

Daily mileage: 88-378 miles
29 additional bus routes

Provide charging for 672 times from 6:05 am to 23:45 pm

➢ Served routes and space-time trajectories of BEBs when five on-route charging stations are built

Previous Effort



332 (111+221) BEBs

Daily mileage: 63-456 miles
67 additional bus routes

Provide charging for 1576 times from 5:30 am to 23:45 pm

➢ Served routes and space-time trajectories of BEBs when 36 on-route charging stations are built

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NITC Project

Optimizing BEB deployment considering cost and environmental equity for disadvantaged population

Problem Formulation:.

- **Objective (1)**: Maximize environmental equity
- **Objective (2)**: Identical as **Objective (0)**
- **Input:** Budget
- **Output:**

1. Locations and number of both in-depot and on-route charging stations
2. Number of buses that were to be replaced
3. The exact buses that were to be replaced

NITC Project

Formulation

$$\max \sum_i E_i Z_i$$

Objective (1)

$$min\ (\sum_i C^B Z_i + \sum_m C_m^O Y_m^O + \sum_m C_n^I Y_n^I)$$

Objective (2)

Constraints:

Subject to

$$D_{i,s-1} + l_{i,s-1,s} \leq R + (1 - Z_i)TD_i \quad (3)$$

$$D_{i,1} = 0, \forall\ i \quad (4)$$

$$D_{i,s} \leq D_{i,s-1} + l_{i,s-1,s}, \forall\ i, s \geq 2 \quad (5)$$

$$D_{i,s} \geq D_{i,s-1} + l_{i,s-1,s} - TD_i X_{is}, \forall\ i, s\ \geq 2 \quad (6)$$

$$D_{i,s} \leq (1 - X_{is})TD_i, \forall\ i, s \geq 1 \quad (7)$$

$$X_{is} \leq Y_m^O, \forall\ m, (i, s) \in \alpha_m \quad (8)$$

$$X_{is} \leq Z_i, \forall\ i, s \quad (9)$$

$$\sum_{(i,s)\in\beta_{mt}} X_{is} \leq\ p^O Y_m^O\ \forall\ m, t \quad (10)$$

$$\sum_{i\in\gamma_n} Z_i \leq\ p^I Y_n^I\ \forall\ n \quad (11)$$

$$X_{is} = 0\ or\ 1, \forall\ i, s \quad (12)$$

$$Z_i = 0\ or\ 1, \forall\ i$$

$$Y_m^O\ and\ Y_n^I\ are\ positive\ integers$$

$$D_{is} \geq 0, \forall\ i, s$$

Zhou, Y., Liu, X. C., Wei, R., & Golub, A. (2020). Bi-Objective Optimization for Battery Electric Bus Deployment Considering Cost and Environmental Equity. *IEEE Transactions on Intelligent Transportation Systems*.

NITC Project

Measure of Environmental Equity -- Ei

- *Intention*: To benefit the disadvantaged population suffered most from air pollution when deploying BEB.
- *Measurement*: Maximize environmental equity ⟷ Maximize weighted population
    - **Weights**: Pollutant (PM 2.5) concentration.
    - **Population**: low-income population.

Ensure that the places where low-income population suffering the most from unhealthy air quality could receive priority in environmental benefits

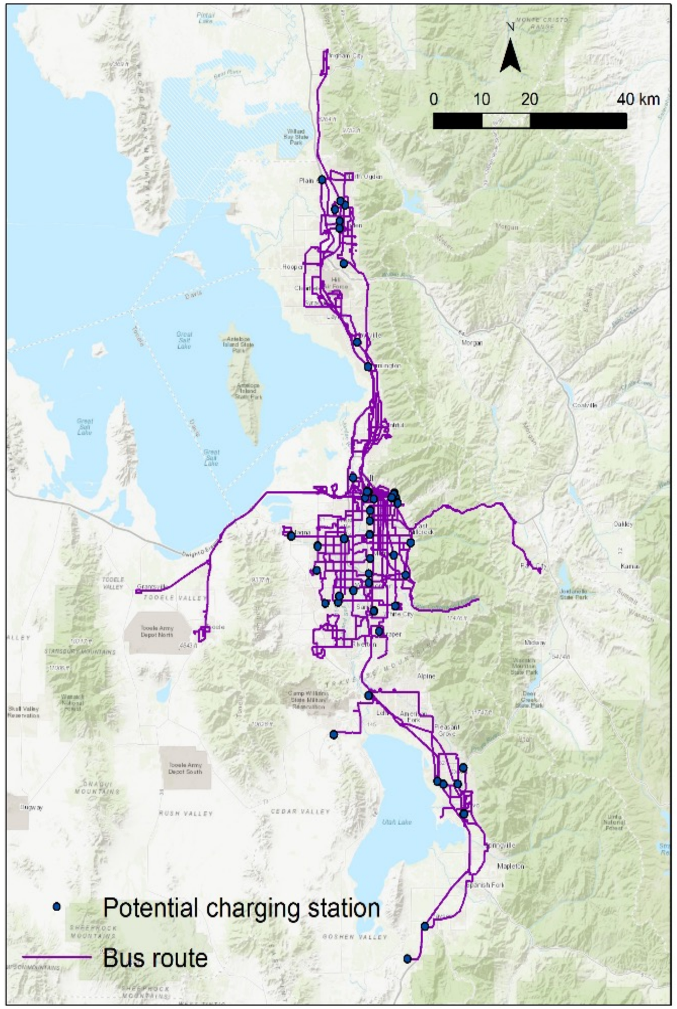
NITC Project

Study Area

- UTA runs 467 diesel or CNG buses serving 121 routes on weekdays

New Flyer’s XE40

- Range: 62-200 miles depending on intensity of battery usage
- On-route charging 10 minutes
- **334** buses among 467 that are eligible for BEB replacement



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Low-income Population

- Data is retrieved from Metropolitan Planning Organizations (MPOs) in Utah for year 2019.
- Low-income group is classified according to 2010 Census income groupings ($0 – $34,999).
- The data is produced at TAZ level.

MPO Boundaries

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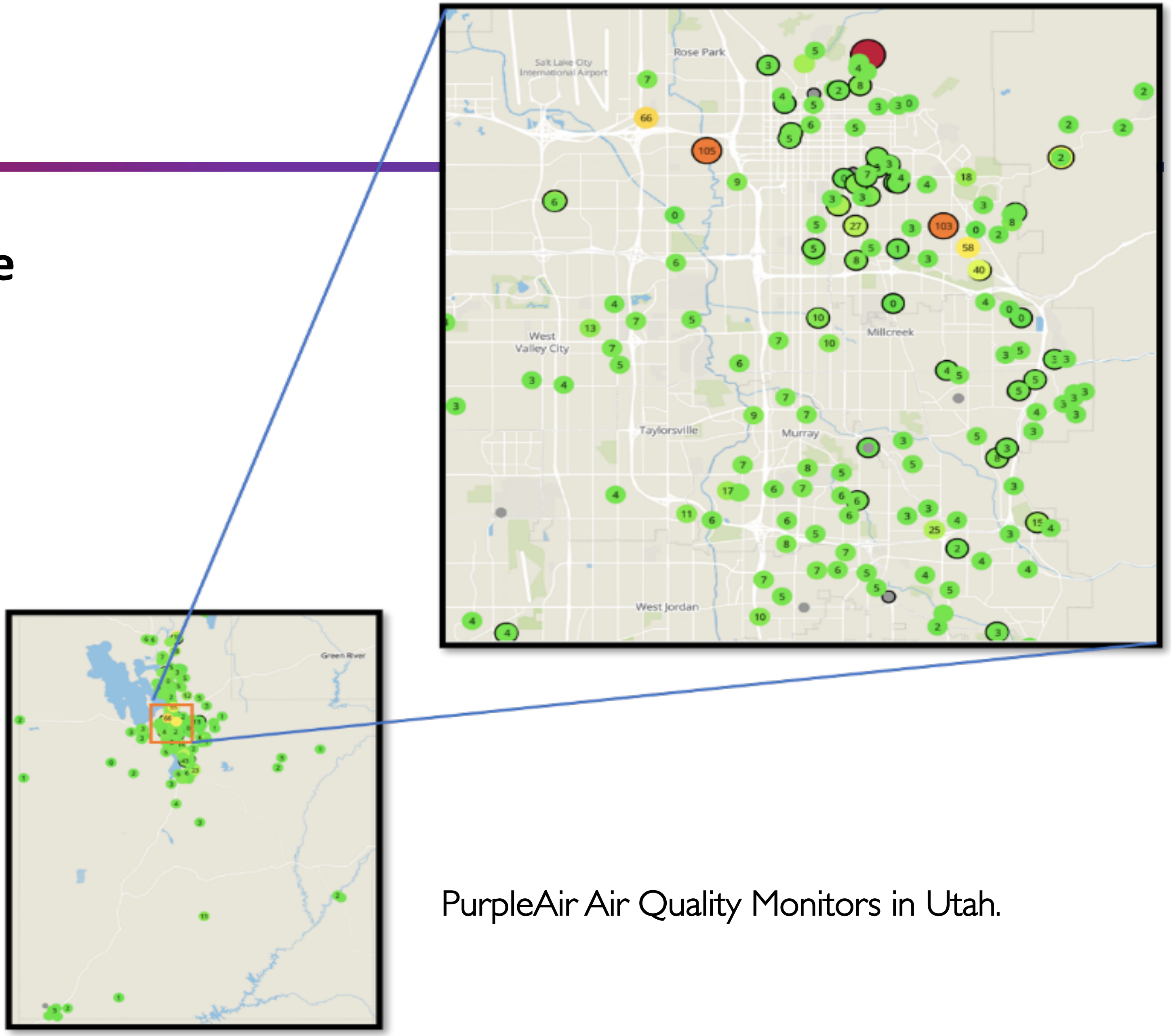
- **PM 2.5 Concentration: Source**



PurpleAir Air Quality Monitors in Utah.

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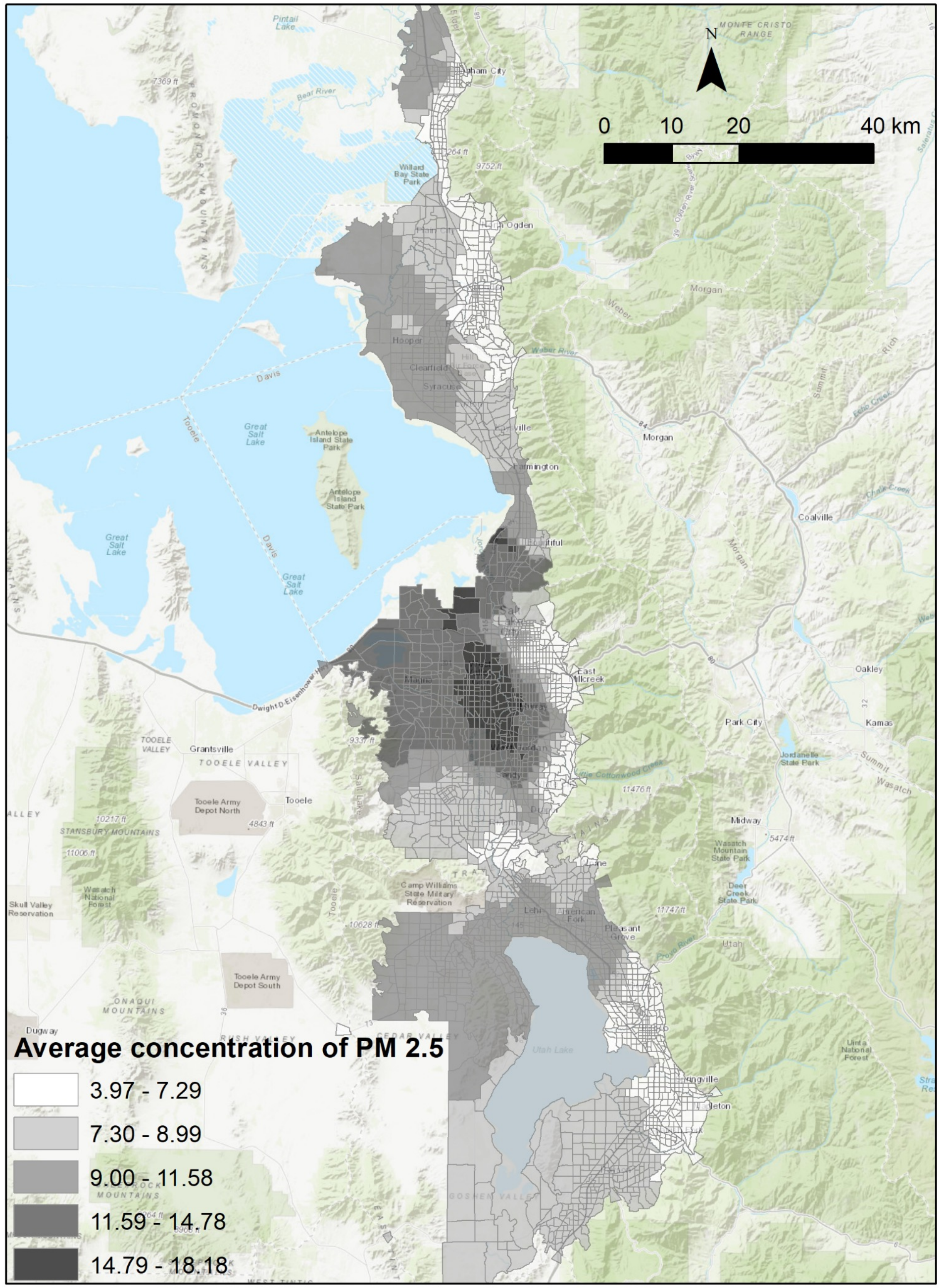
- **PM 2.5 Concentration: Result**

Averaged at TAZ level



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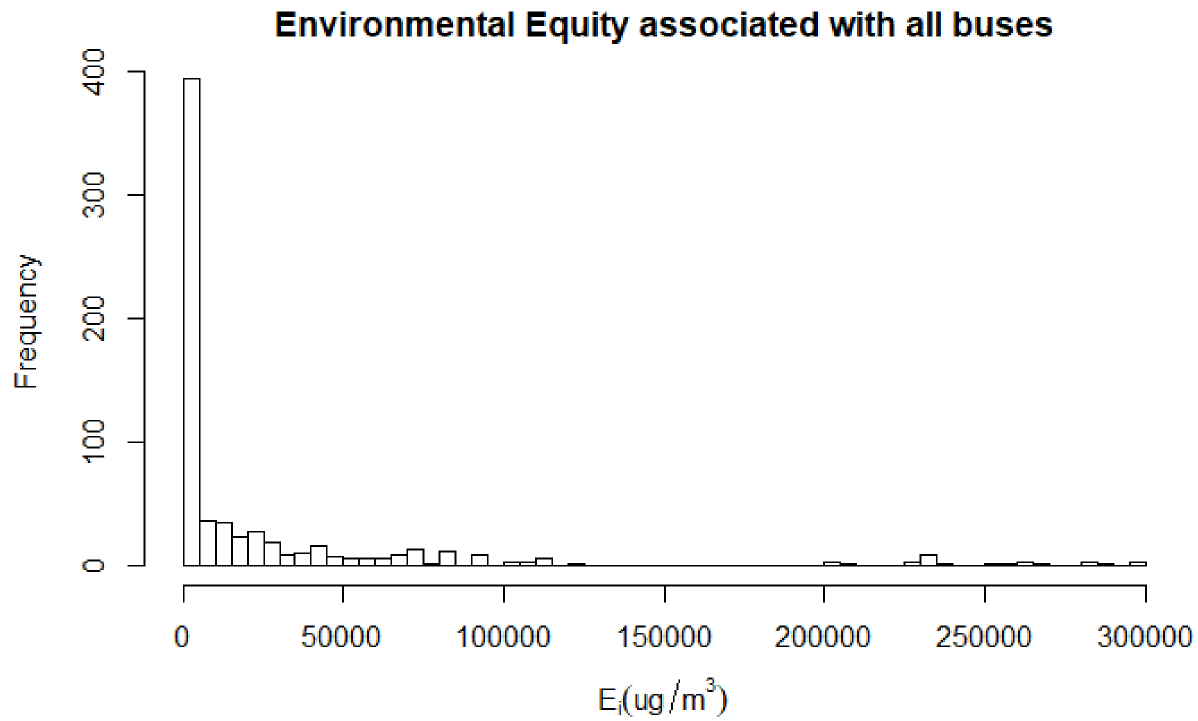
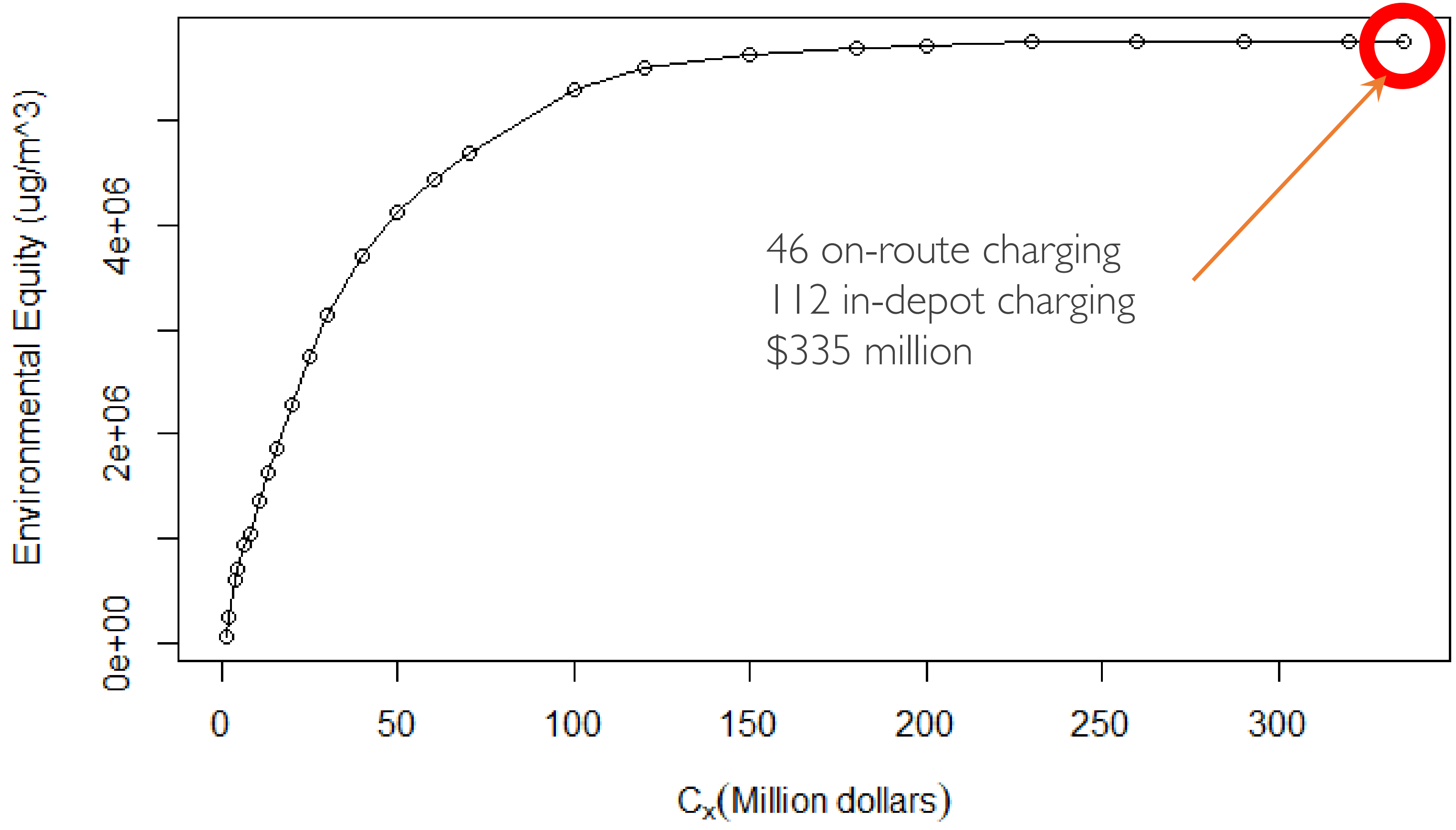


Environmental equity associated with 90% of buses are below 25,000 ug/m^3

- **Highly Imbalanced.**
- **Major contribution comes from a few buses.**

Trade-off between Cost and Environmental Equity



In-deport charging: 3 BEBs simultaneously, $350,000
On-route charging: 1 BEB only, $1,000,000
XE40: $790,000

334 buses for replacement

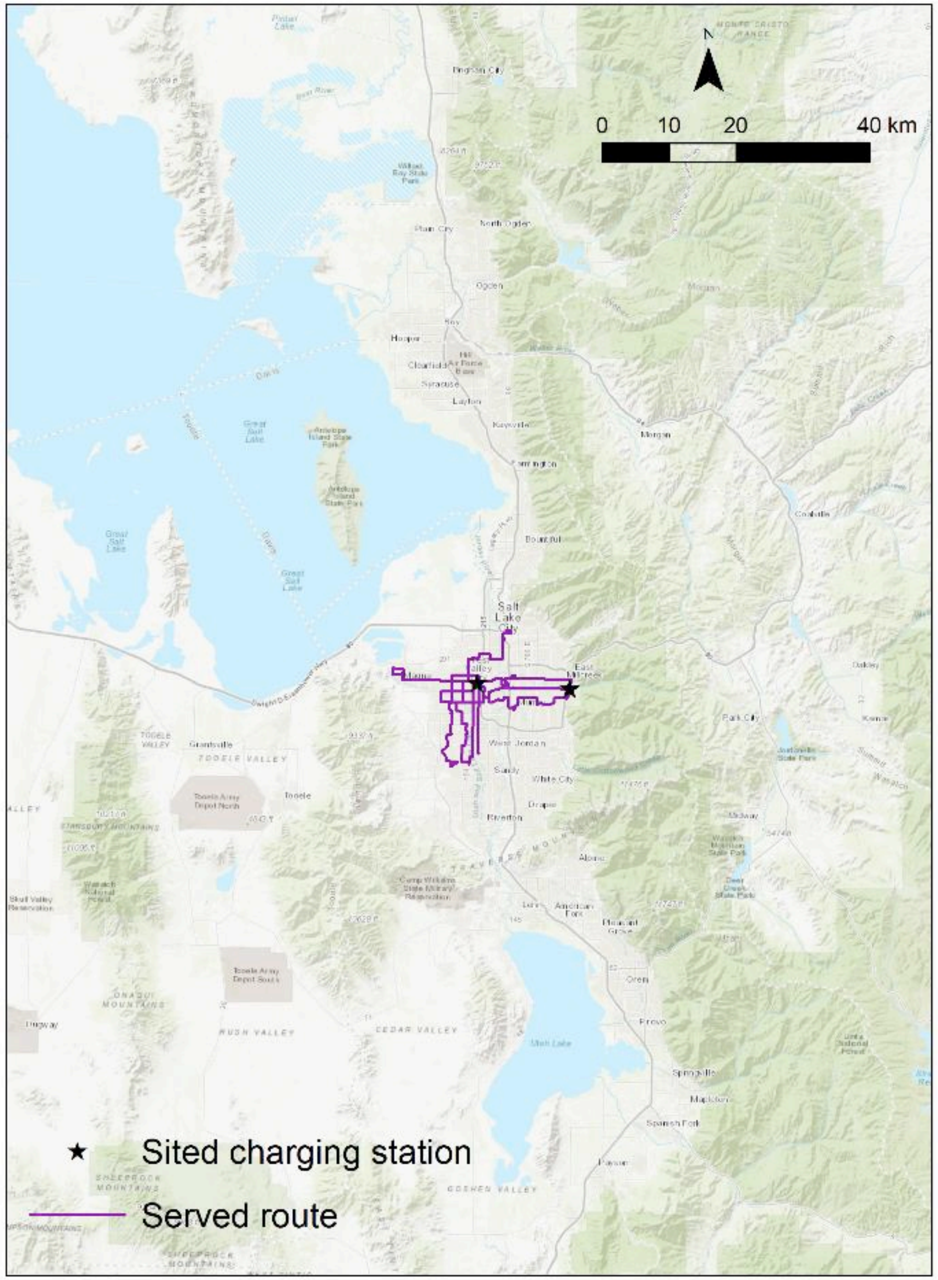
3 Application 1

BEB deployment plan when budget is set at $25 million

26 BEBs
2 on-route charging
9 in-depot charging

West Valley Central Station and Millcreek

The daily mileage of the buses ranges from 161.89 miles to 263.33 miles with an average of 202.98 miles



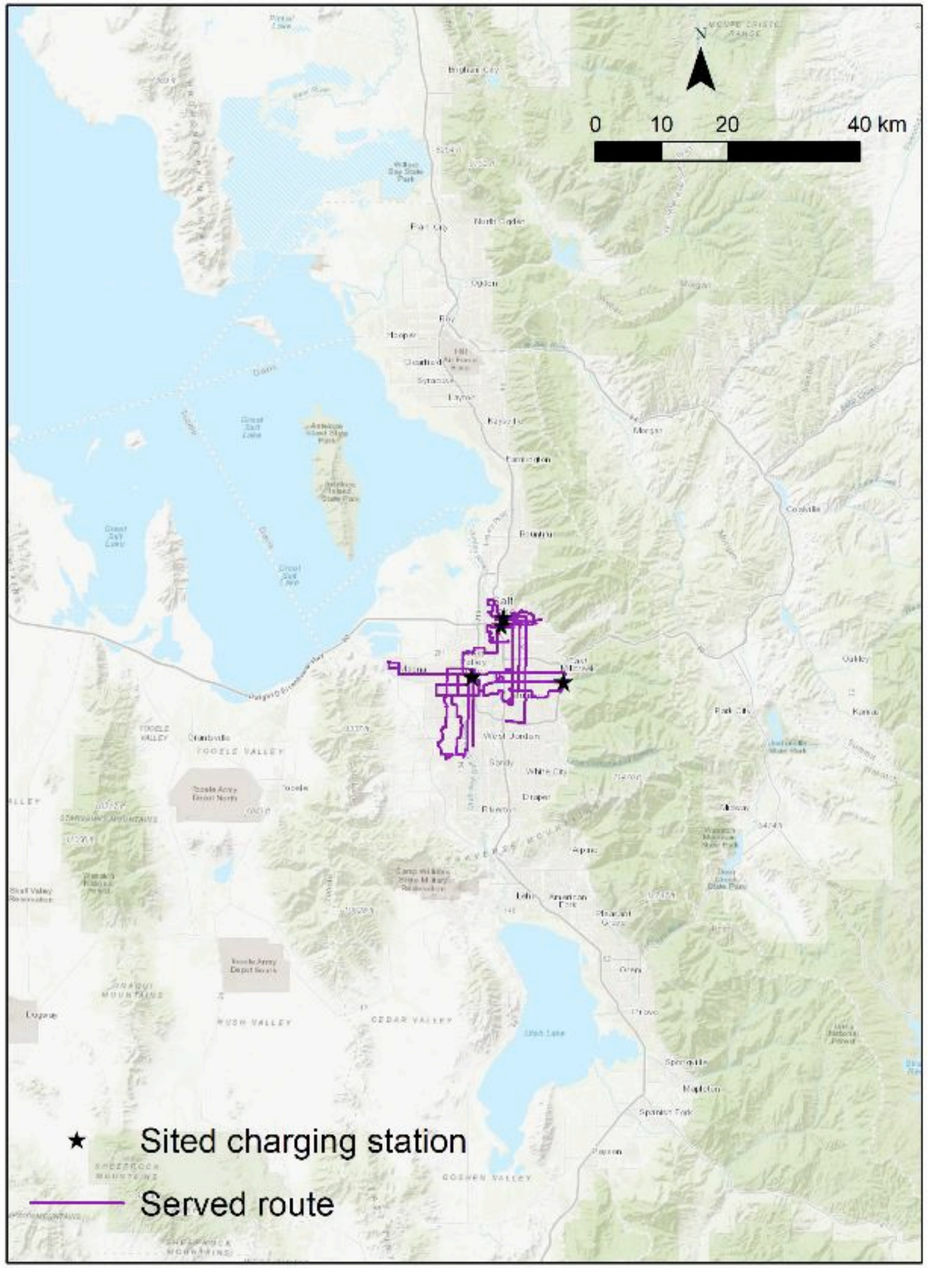
3 Application 2

BEB deployment plan when budget is set at $60 million.

63 BEB
5 on-route charging
21 in-depot charging

West Valley Central Millcreek, and North Temple, SL Central

The daily mileage of the buses ranges from 62.78 miles to 263.33 miles with an average of 176.2 miles



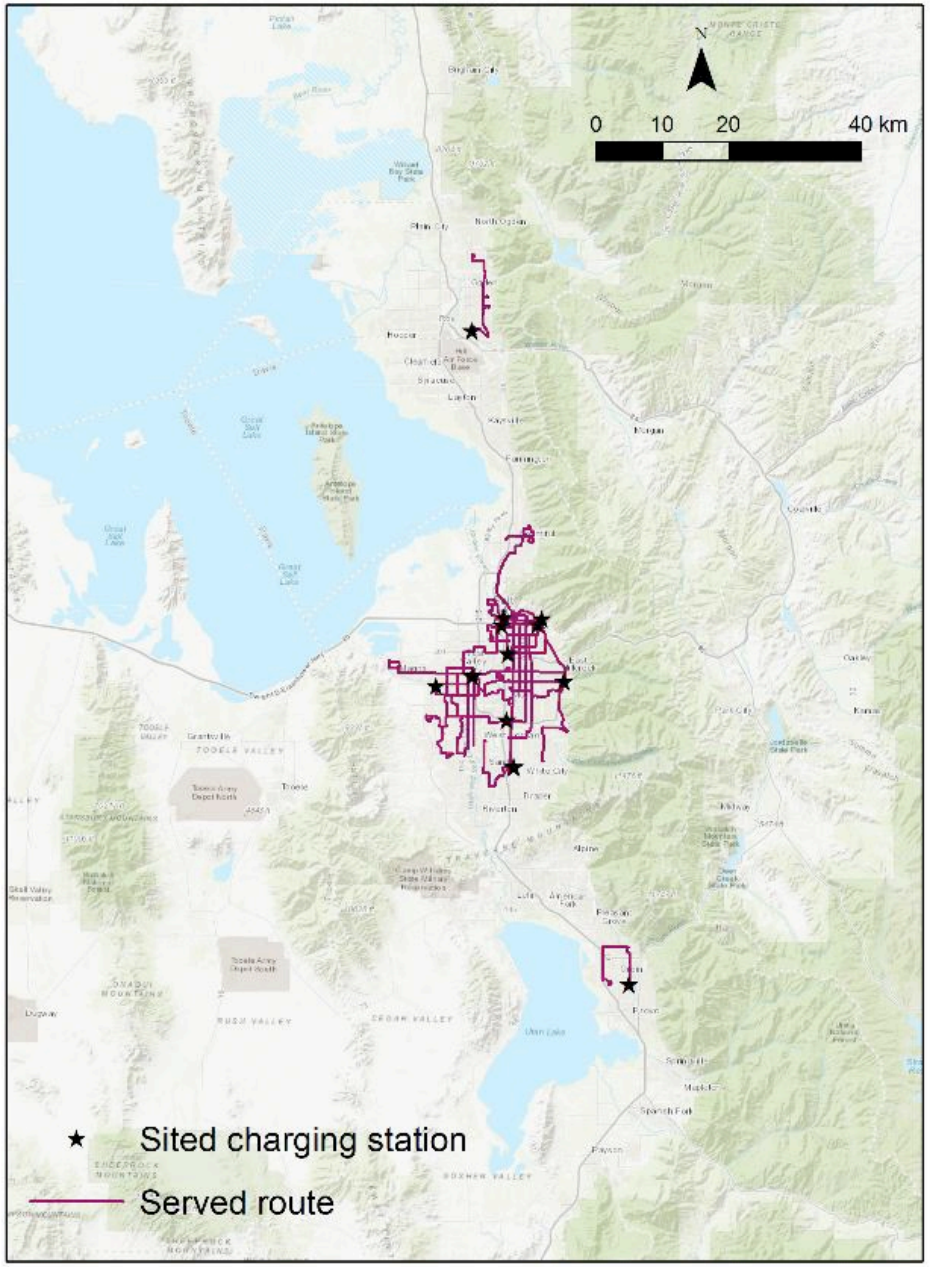
3 Application 3

BEB deployment plan when budget is set at $120 million

122 BEB
14 on-route charging
41 in-depot charging

West Valley Central Millcreek, and North Temple, SL Central, Murry, Ogden, Orem

The daily mileage of the buses ranges from 62.78 miles to 263.33 miles with an average of 170.52 miles



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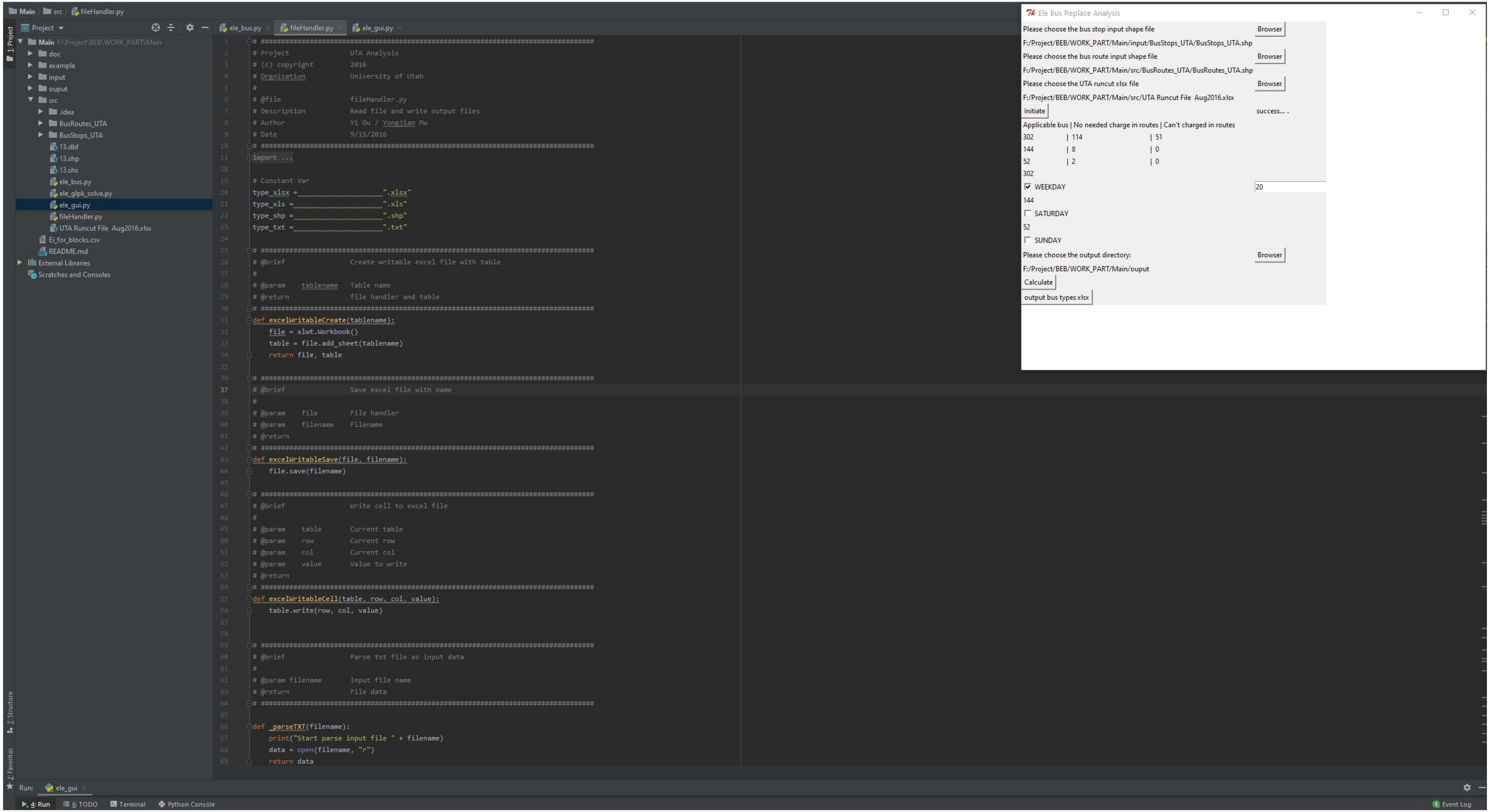
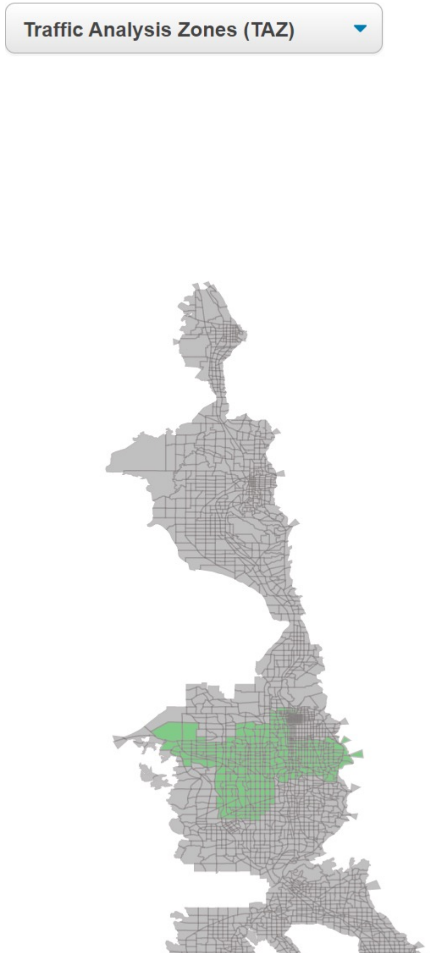
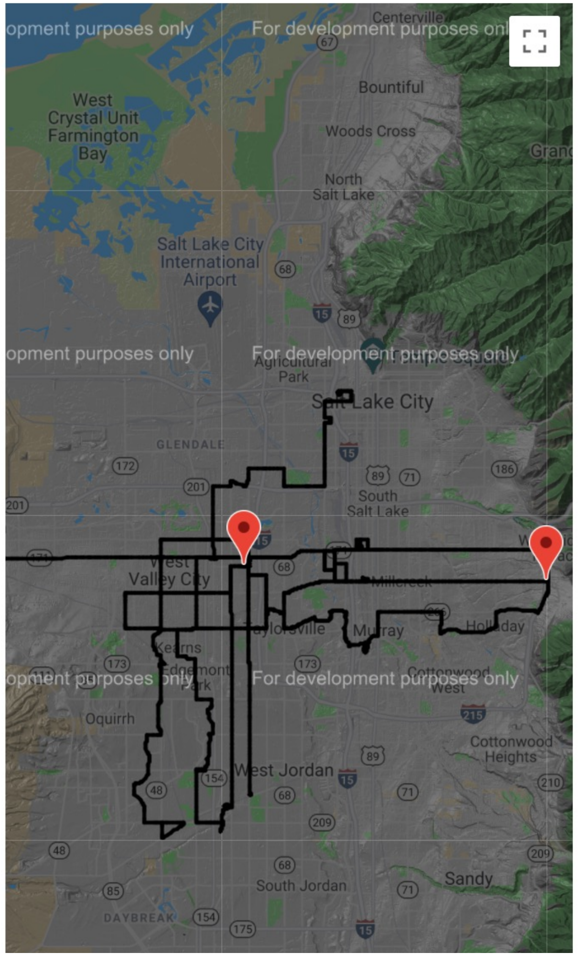
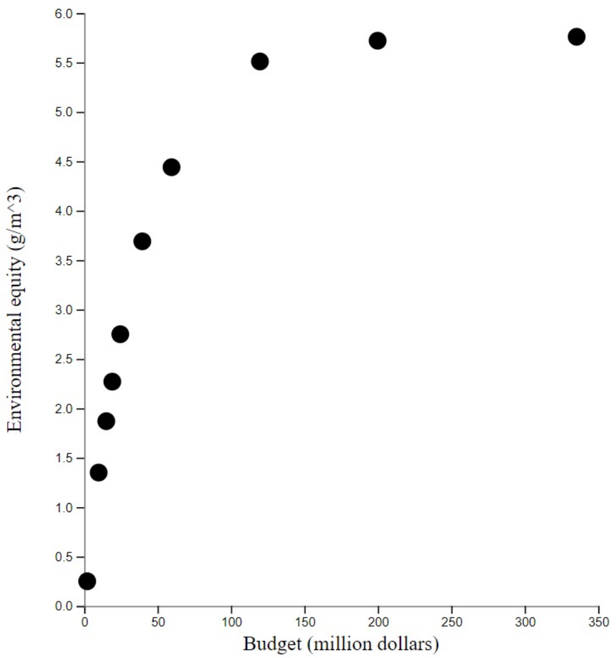

Main src fileHandler.py
Project
ele_bus.py
fileHandler.py
ele_gui.py
Main F:\Project\BEB\WORK_PART\Main
doc
example
input
ouput
src
.idea
BusRoutes_UTA
BusStops_UTA
13.dbf
13.shp
13.shx
ele_bus.py
ele_glpk_solve.py
ele_gui.py
fileHandler.py
UTA Runcut File Aug2016.xlsx
Ei_for_blocks.csv
README.md
External Libraries
Scratches and Consoles
##
Project UTA Analysis
(c) copyright 2016
Orgnization University of Utah
#
@file fileHandler.py
Description Read file and write output files
Author Yi Ou / Yongjian Mu
Date 9/15/2016
##
import ...
# Constant Var
type_xlsx = ".xlsx"
type_xls = ".xls"
type_shp = ".shp"
type_txt = ".txt"
# ##
# @brief Create writable excel file with table
#
# @param tablename Table name
# @return file handler and table
# ##
def excelWritableCreate(tablename):
file = xlwt.Workbook()
table = file.add_sheet(tablename)
return file, table
##
@brief Save excel file with name
#
# @param file File handler
# @param filename Filename
# @return
# ##
def excelWritableSave(file, filename):
file.save(filename)
# ##
# @brief Write cell to excel file
#
# @param table Current table
# @param row Current row
# @param col Current col
# @param value Value to write
# @return
# ##
def excelWritableCell(table, row, col, value):
table.write(row, col, value)
# ##
# @brief Parse txt file as input data
#
# @param filename Input file name
# @return File data
# ##
def _parseTXT(filename):
print("Start parse input file " + filename)
data = open(filename, "r")
return data
Ele Bus Replace Analysis
Please choose the bus stop input shape file
Browser
F:/Project/BEB/WORK_PART/Main/input/BusStops_UTA/BusStops_UTA.shp
Please choose the bus route input shape file
Browser
F:/Project/BEB/WORK_PART/Main/src/BusRoutes_UTA/BusRoutes_UTA.shp
Please choose the UTA runcut xlsx file
Browser
F:/Project/BEB/WORK_PART/Main/src/UTA Runcut File Aug2016.xlsx
Initiate
success... .
Applicable bus | No needed charge in routes | Can't charged in routes
302 | 114 | 51
144 | 8 | 0
52 | 2 | 0
302
WEEKDAY
20
144
SATURDAY
52
SUNDAY
Please choose the output directory:
Browser
F:/Project/BEB/WORK_PART/Main/ouput
Calculate
output bus types xlsx
Run: ele_gui
4: Run
6: TODO
Terminal
Python Console
Event Log

https://duskdeep.github.io/

Battery Electric Bus Deployment in the Greater Salt Lake Region







5

Conclusions

At the initial deployment phase, charging stations and BEBs can be selected at highly dense service locations - a favorable choice for locations with larger population and job density that are serviced by high density transit network

As number of BEBs increases, the expansion results in a wider coverage of the network, extending to outskirts, to serve low-density service areas with fewer number of buses

Transit agencies would be able to make planning-level decisions based on their short- and long-term strategic goals (e.g. how many BEBs are needed in the next 5, 10, and 20 years) and resources (budget level in the next 5, 10, 20 years) to find the investment tipping point

The model can be extended to incorporate additional goals other than budget and environmental equity achieved such as maximizing service area, fuel efficiency, robustness of the system, etc.